

Development of high efficiency Stirling-type pulse tube cryocoolers

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ABSTRACT

Thermoacoustic theory is a powerful tool to understand the working mechanism of regenerative thermoacoustic systems. In this paper, a modified thermoacoustic model is employed to design three single-stage Stirling-type pulse tube cryocoolers. The first one (PTC-10) is designed with in-line configuration and the second one (CPTC-10) is designed with co-axial configuration. Both of them are able to provide about 10 W cooling power at 77 K with a relative Carnot efficiency of about 18.6%. The third one (PTC-20), designed with in-line configuration, has a twice cross section area of the PTC-10. It can provide more than 20 W cooling power at 77 K with a relative Carnot efficiency of 22%.

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1. Introduction

A Stirling-type pulse tube cryocooler (PTC) mainly includes two parts: a linear compressor and a pulse tube cold finger. In the linear compressor, electric power is converted into acoustic power in form of oscillating flow with a high frequency. The linear compressor has less friction than conventional rotary valveless compressor. In the pulse tube cold finger, acoustic power is consumed to produce refrigeration effect without any moving parts. The combination of the two technologies forms a Stirling-type pulse tube cryocooler which promises high efficiency, high reliability and small size. Because of these significant advantages, this kind of cryocooler has applications of cooling aerospace devices.

In the past decades, much effort has been paid to PTC. In 1999, Radebaugh reviewed the development of PTCs [1], it was found that the relative Carnot efficiency of most PTC prototypes is less than 15%. In 2000, Marquardt et al. constructed a pulse tube oxygen liquefier. Its relative Carnot efficiency of the acoustic power to cooling power reached 20% at 90 K. However, the PTC's compressor did not match the cold finger well, so the relative Carnot efficiency of the whole system is only about 13% [2]. Recently, with better understanding on the coupling mechanism between the pulse tube cold finger and the linear compressor, the relative Carnot efficiency has been improving. In 2002, Tward et al. developed a PTC with 10 W cooling power at 95 K with a relative Carnot efficiency of 17% for a whole system [3]. In 2005, Praxair Inc. reported a PTC producing 300 W cooling power at 80 K with 4.3 kW input

electric power, corresponding to a relative Carnot efficiency of 19.2% [4].

Because of the requirement of cryocoolers working at 77 K, we started to develop Stirling-type pulse tube cryocoolers driven by linear compressor since last year. In this paper, three single-stage Stirling-type PTCs will be introduced. The first one (PTC-10) was designed with in-line configuration and the second one (CPTC-10) was designed with co-axial configuration. The two PTCs can offer about 10 W cooling power at 77 K. They reached a relative Carnot efficiency of 18.6% based on our measurements. In addition, a larger one (PTC-20) was developed. It can provide more than 20 W cooling power at 77 K with a highest relative Carnot efficiency of 22%.

2. Theoretical model

In the past 10 years, our work mainly focused on thermoacoustic prime movers and refrigerators. Thermoacoustic theory is the main theoretical tool that we used to understand the working mechanism of regenerative systems. So the model that we employed to design the cold finger is based on thermoacoustic theory in this paper. According to thermoacoustic theory, the flow in the cold finger can be described with following three equations [5,6]:

$$dU/dx + (i\omega\zeta_c c + 1/\zeta_k r_k)p + ZU = 0 \quad (1)$$

$$dp/dx + (\zeta_\mu r_\mu + i\omega\zeta_l l)U = 0 \quad (2)$$

$$dH/dx = -Q \quad (3)$$

where p , U are the pressure and volume flow rate, H is the total energy flow, Q is the heat transfer between each component and the

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surroundings, ω is the angular frequency. r_μ , l , c , r_k present the viscous resistance, inertance, compliance and thermal-relaxation resistance per unit length, respectively. Z is a function about the temperature gradient in the flow channel. Its expression is presented in [7]. The thermoacoustic theory developed by Rott is based on hypothesis of laminar flow [8]. For a practical PTC, its inertance tube phase shifter is often dominated by turbulent flow, so the coefficient of correction ξ is introduced in Eqs. (1) and (2). The details of determination of ξ are presented in Ref. [9].

If the thermodynamic element is divided into a certain number of cells as shown in Fig. 1, by analytically solving Eqs. (1) and (2), the relationship of two neighboring cells can be rewritten as:

$$\begin{bmatrix} P_{(n+1)} \\ U_{(n+1)} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} P_n \\ U_n \end{bmatrix} \quad (4)$$

Here, A is a 2×2 transfer matrix. For Eq. (3) it can be written in a discrete form,

$$B_1 T_{(n-1)} + B_2 T_{(n)} + B_3 T_{(n+1)} = B_4 \quad (5)$$

The expressions of A and B are complicated and readers can find the expressions in Ref. [10]. Combining this form of equation of all the computational cells leads to a sparse matrix which can be easily solved using linear algebra algorithms.

In the calculation, the initial temperature distribution is firstly assumed, and P and U of all cells can be calculated from Eq. (4). Then Eq. (5) is used to calculate the new temperature values. According to the results, the temperature distribution is modified. Since elements of the matrix in Eq. (4) are functions of temperature, P and U need to be recalculated. This iteration process should be continued until $|(T_k - T_{k-1})/T_k| \leq 0.01$ is met as shown in Fig. 2 [5,9]. T_k and T_{k-1} are the temperatures in two consecutive iterations.

The efficiency of the compressor η is influenced by the acoustic resistance of the cold finger. The relationship can be expressed as [11]:

$$\frac{1}{\eta} = 1 + \frac{R_{\text{mech}}}{A^2 R_{\text{acoust}}} + \frac{R_{\text{elec}}}{R_{\text{acoust}}} \frac{A^2}{\tau^2} \left(R_{\text{acoust}} + \frac{R_{\text{mech}}}{A^2} \right)^2 \quad (6)$$

where τ is the transduction coefficient, A is the area of the piston, R_{mech} , R_{acoust} , R_{elec} are the mechanical resistance of the compressor, the acoustic resistance of the cold finger and electric impedance of the coil, respectively.

3. Numerical results

Fig. 3 is the schematic of the PTC-10. The compressor is provided by Zhongke Lihan Inc. It is dual-opposed piston designed, which can minimize vibration. The cold finger is mainly composed

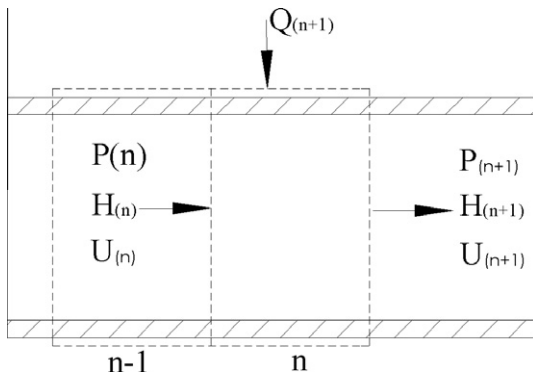


Fig. 1. Schematic of the calculated cells.

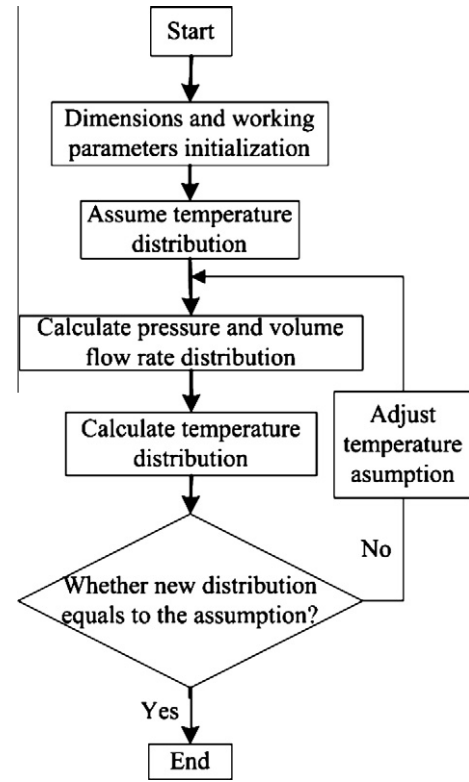


Fig. 2. Structure of the numerical program.

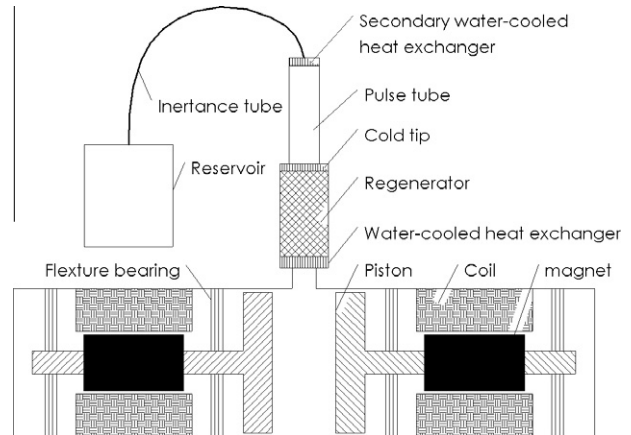


Fig. 3. Schematic of PTC-10 and PTC-20.

of water-cooled heat exchangers (WHE), cold tip (CT), regenerator (RG), pulse tube (PT), inertance tube and reservoir. In the numerical simulation, the mean pressure is 2 MPa, the frequency is 50 Hz, the heat sink and cooling temperatures are 298 K and 77 K.

According to the electrical-mechanical parameters of the linear compressor, Fig. 4 shows the dependence of the compressor efficiency on the acoustic resistance of the cold finger in the PTC-10. When the acoustic resistance is bigger than $10 \times 10^7 \text{ Pa s/m}^3$, the compressor efficiency decreases slowly; when the resistance is less than $7 \times 10^7 \text{ Pa s/m}^3$, the compressor efficiency decreases rapidly. So the acoustic resistance of the cold finger in PTC-10 is set as $9 \times 10^7 \text{ Pa s/m}^3$. In the simulation of the cold finger, the cross section area of the regenerator can be adjusted to satisfy the requirement of the acoustic resistance.

By optimizing the regenerator and the pulse tube to satisfy the requirement of the acoustic resistance and to improve the effi-

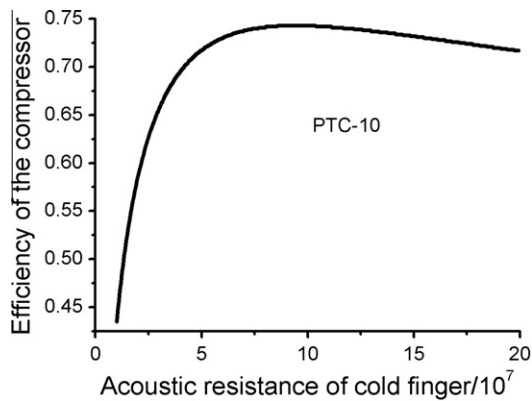


Fig. 4. Dependence of compressor efficiency on the acoustic resistance.

ciency of the cold finger, the dimensions of the cold finger are fixed as shown in Table 1. The cold finger can obtain 9.7 W cooling power at 77 K with 88.5 W acoustic power input. The relative efficiency of Carnot reaches 23.5% assuming the compressor efficient of 75%. Figs. 5–8 show the temperature, pressure, volume flow rate and phase angle of pressure leading flow distribution in the cold finger. Generally, the temperature distribution in the pulse tube is supposed to be linear. But the numerical result shows that this is not true as shown in Fig. 5. Because of the acoustic power dissipating and the weak heat pumping effect in a practical pulse tube, the average temperature is higher than the linear distribution. In Fig. 6, it can be seen that the pressure drop mainly comes from the regenerator. In the water-cooled heat exchanger and the pulse tube, the pressure drop is almost zero. The volume flow rate drops about 15% in the water-cooled heat exchanger, and it drops severely in the regenerator with the decreasing of the temperature. In the pulse tube, the volume flow rate increases with the temperature as shown in Fig. 7. At the inlet of the water-cooled heat exchanger, the flow leads the pressure about 40°, meanwhile at the outlet of the cold tip, the pressure leads the flow about 40°. At the middle point of the regenerator, the pressure and the flow are in phase. At the outlet of the secondary water-cooled heat exchanger, the pressure leads the flow about 70°. Such a big phase angle in relative small PTCs generally cannot be realized by an inertance tube, so it can be predicted that the practical performance of the PTC will not be so good as the numerical result.

4. Experimental result

In the three PTCs, the heat exchangers at the hot ends of the regenerator and the pulse tube are both cooled by water. The vacuum chamber of the cryocooler is maintained at 10^{-3} Pa by a turbo-molecular pump. The temperatures of the cold tips are measured by calibrated platinum (PT100) resistance thermometers with an accuracy of ± 0.1 K. A constantan wire heated by a direct voltage source is mounted on each cold tip to simulate the heating load. The input electric power is calculated from the voltage and current data of the compressor acquired through a self-developed program based on Labview 7.1 of National Instruments Inc.

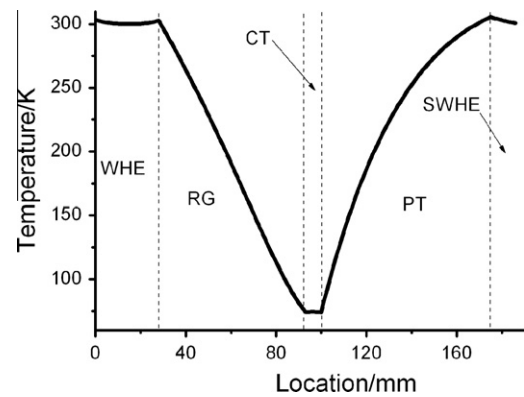


Fig. 5. Temperature distribution.

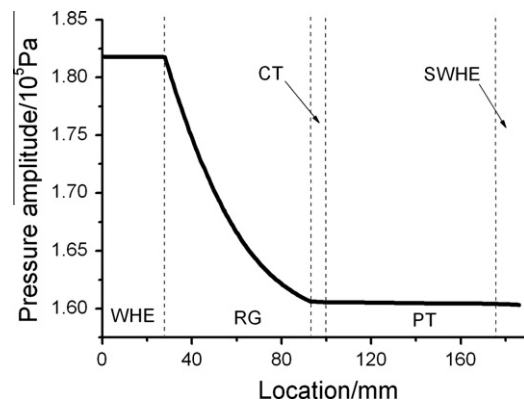


Fig. 6. Pressure amplitude distribution.

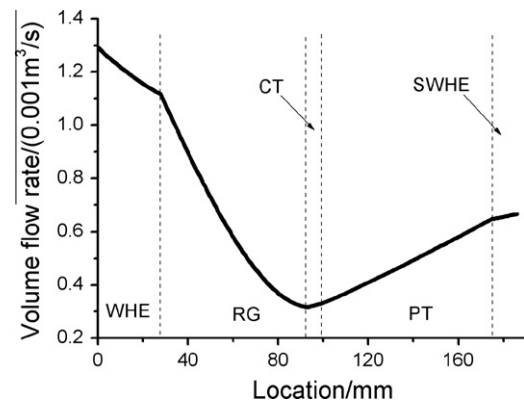


Fig. 7. Volume flow rate distribution.

Fig. 3 is the schematic of the PTC-10. Table 1 presents the dimensions. The regenerator is 30 mm in diameter and 65 mm in length. It is filled with 300 mesh stainless steel wire screen. The pulse tube is 20 mm in diameter and 75 mm in length. The inertance tube is 3.5 mm in diameter and 2.2 m in length. The volume

Table 1
The main dimensions of PTC-10.

	Water-cooled heat exchanger	Regenerator	Cold tip	Pulse tube	Secondary water-cooled heat exchanger	Inertance tube
PTC-10	$\Phi 30 \times 28$	$\Phi 30 \times 65$	$\Phi 20 \times 7$	$\Phi 20 \times 75$	$\Phi 20 \times 11$	$\Phi 3.5 \times 2200$
PTC-20	$\Phi 43 \times 28$	$\Phi 43 \times 65$	$\Phi 25 \times 7$	$\Phi 25 \times 75$	$\Phi 25 \times 11$	$\Phi 5.5 \times 3000$

The listed dimensions are: inner diameter $\times$ length (all in mm).

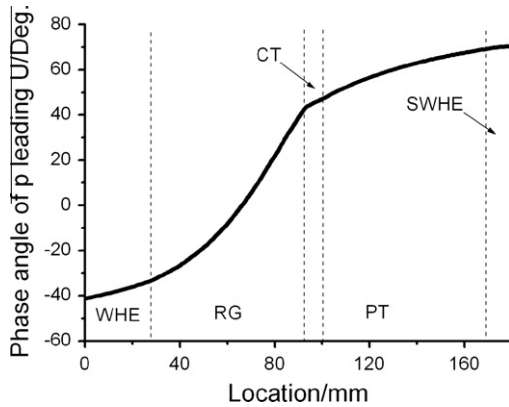


Fig. 8. Phase angle of pressure leading flow distribution.

of the reservoir is 1 L. The heat exchangers are similar to those in Ref. [12]. They are made of copper and include machined radialized slots using an electron discharge machining technique (EDM). Compared to other techniques such as, shells and tubes, counter flow tubes heat exchangers, stacked copper meshes, this offers the best compromise between heat transfer, pressure drop and dead volume. The compressor was provided by Zhongke Lihan Inc. with a maximum input electric power of about 200 W. The average pressure is 2 MPa and the working frequency is 50 Hz. Figs. 9 and 10 show the cooling performance of PTC-10. With 120 W input power, the cooling power is 8.1 W at 77 K with a reject temperature of 283 K. The lowest cooling temperature is 42.1 K. At 60 K, the cooling power is 3.9 W. If the input power is increased to 178 W (the pressure ratio at the front of the piston is

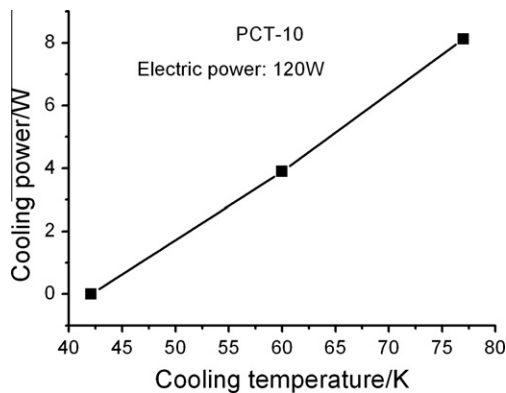


Fig. 9. Temperature dependence of cooling power of PTC-10.

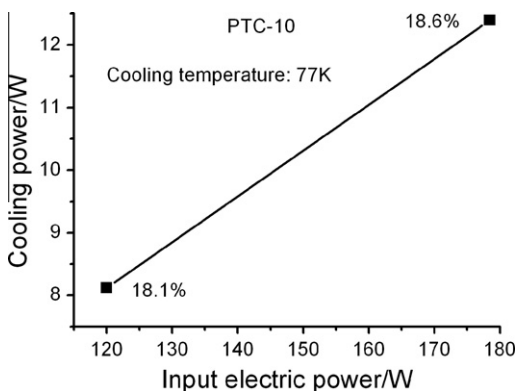


Fig. 10. Input electric power dependence of cooling power of PTC-10.

1.19), the cooling power reaches 12.4 W at 77 K, corresponding a relative efficiency of Carnot of 18.6%.

In order to make the PTC more compact, a co-axial PTC named CPTC-10 is designed. The compressor, the inertance tube, the reservoir, cross section area of the regenerator and pulse tube are all the same as those of the PTC-10. The average pressure and the frequency are also kept the same. Figs. 11 and 12 show the cooling power of CPTC-10. At 77 K, the highest efficiency of Carnot is 18.6%, achieving the same efficiency as PTC-10.

The configuration of PTC-20 is the same as the in-line PTC-10 but with different cross sectional area. The cross section area of the regenerator is twice of that of PTC-10. The inertance tube is

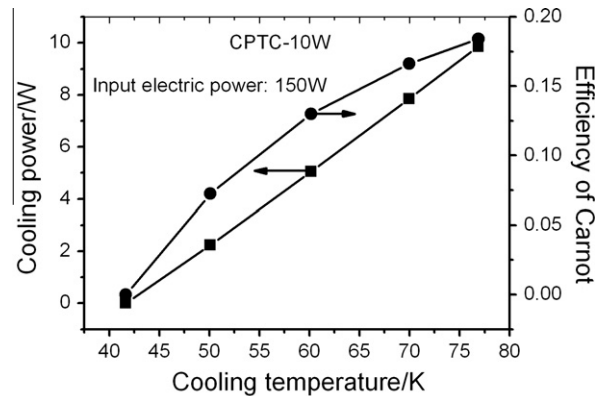


Fig. 11. Temperature dependence of cooling power of CPTC-10.

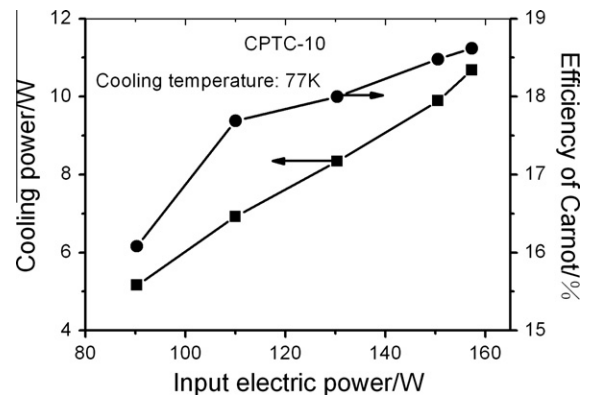


Fig. 12. Input electric power dependence of cooling power of CPTC-10.

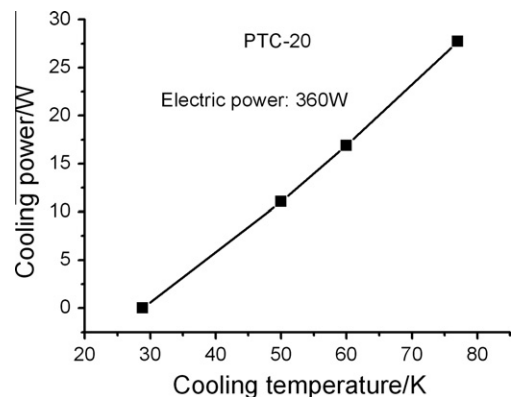


Fig. 13. Temperature dependence of cooling power of PTC-20.

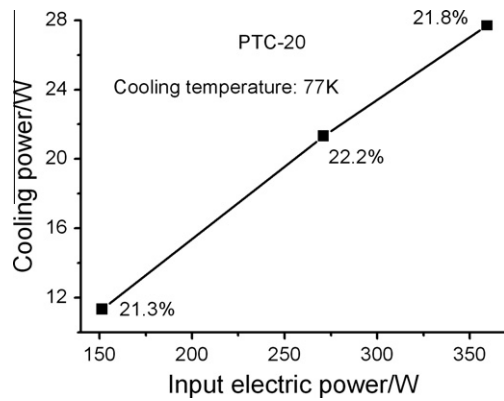


Fig. 14. Input electric power dependance of cooling power of PTC-20.

5.5 mm in diameter and 3 m in length. The volume of the reservoir is 1 L. The maximum input electric power of the compressor is 400 W. The average pressure is 2 MPa and the working frequency is 50 Hz. Figs. 13 and 14 show the cooling performance. The lowest cooling temperature is 28.8 K and 27.7 W cooling power at 77 K can be obtained with 360 W input electric power. Because the inertance tube is easier to offer the ideal phase shift in PTCs with higher cooling power, the PTC-20 reaches a relative Carnot efficiency of 22%.

5. Conclusions

A modified thermoacoustic model is employed to optimize pulse tube cryocoolers and a numerical method is presented in this paper. The coupling mechanism between the pulse tube cod finger and the linear compressor was discussed. In addition, three high efficient PTCs were developed based on this model. In the two PTCs with a capacity of 10 W cooling power at 77 K, a relative Carnot

efficiency of 18.6% was obtained. In the PTC with a capacity of 20 W cooling power, the efficiency reached 22%.

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